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Damage Ratio of Water Pipes during the 2007 Niigata-Ken Chuetsu-Oki, Japan, Earthquake

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Abstract

This study investigates the relationship between damage ratios of water pipes and seismic motion intensity after the 2007 Niigata-ken Chuetsu-oki, Japan, earthquake. The damage ratios of water distribution pipelines within a 2 km radius from the seismic observation stations are calculated in Kashiwazaki City, Niigata Prefecture. The damage ratios are compared with the fragility curves that were empirically obtained after the 1995 Kobe earthquake. On the other hand, the damage ratios for the greater area are obtained with respect to the estimated seismic motion intensities. Based on the results, regression analyses are performed to reveal the characteristics of damage incidents to water pipes during the event.

Keywords: water pipes; The 2007 Niigata-ken Chuetsu-oki earthquake; seismic motion; fragility curve; GIS.

1. INTRODUCTION

To estimate damage ratios of water distribution pipelines, fragility curves were empirically obtained based on the damage datasets after the 1995 Kobe earthquake. Unfortunately, the number of seismometers was limited at that time. Since the 1995 Kobe earthquake, the number of seismometers has increased and various kinds of nationwide spatial data have become available. Under these circumstances, the methodology to estimate seismically-induced damages can be revised with analyzing the damage datasets from recent earthquakes.

This study investigates the relationship between damage ratios of water pipes and seismic motion intensities after the 2007 Niigata-ken Chuetsu-oki, Japan, earthquake combined with various nationwide

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spatial data. The relationship revealed in this study is compared with the fragility curves that were empirically obtained after the 1995 Kobe earthquake. Based on the results, the characteristics of damage ratio of water distribution pipelines are discussed.

2. INTEGRATION OF VARIOUS SPATIAL DATASETS ON GIS

Geographic Information Systems (GIS) are often used to analyze the damage incidents to lifeline systems during earthquakes (Jeon and O'Rourke, 2005; Kuwata *et al.,* 2008). This study also uses GIS to investigate the damage datasets after the 2007 Niigata-ken Chuetsu-oki earthquake.

Damage datasets of water pipelines were collected and they were integrated into ArcGIS 9.3. The datasets include the information of water pipes (e.g., location, pipe material, diameter) in Kashiwazaki City, Niigata Prefecture subjected to severe seismic motion during the earthquake. In this dataset, the locations of damage occurrences are also available. The number of damage incidents to water pipes is 554. The total length of water pipelines is 852.6 km in Kashiwazaki city (excluding Nishiyama-cho). The geomorphological land classification map used in this study is 1:50000 scale, the digital map for Kashiwazaki - Higashi-Kubiki region developed by Takeuchi and Kawabata (2007). The integrated GIS datasets are shown in Fig. 1.

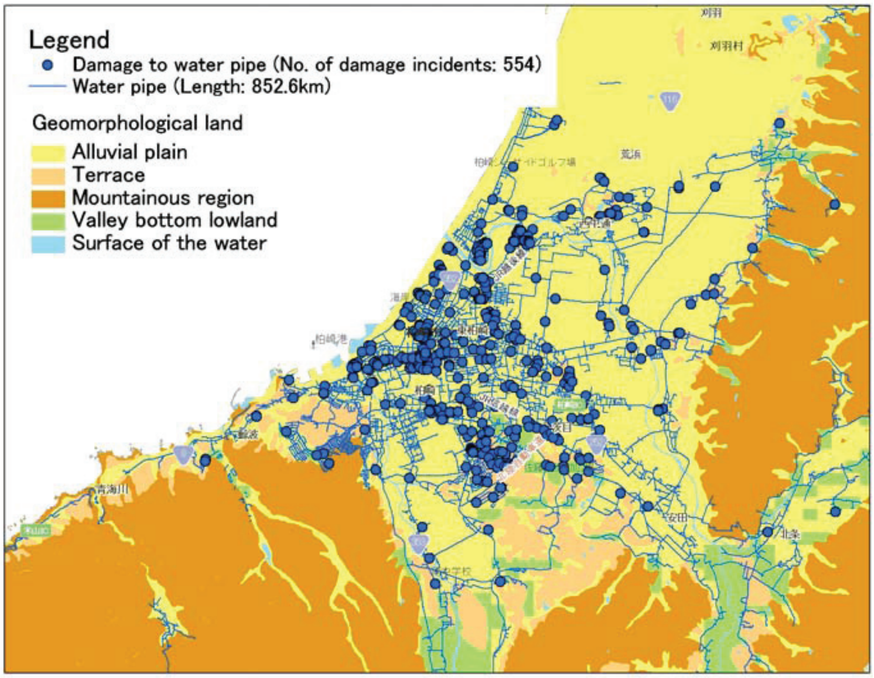


Figure 1: Location of damage occurrence to water pipes in Kashiwazaki city and its geomorphological land classifications.

3. FRAGILITY CURVES OF WATER DISTRIBUTION PIPELINES

To estimate the damage ratio of water distribution pipelines (i.e., the number of damage incidents per kilometer of water pipline), Isoyama *et al.* (2000) employed the following formula:

$$R_m(v) = C_p C_d C_g C_l R(v). \tag{1}$$

Where R_m is the damage ratio; C_p, C_d, C_g, and C_l are correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence, respectively. v is the peak ground velocity (PGV).

$R(v)$ estimates the damage ratio for cast iron pipe (CIP) with a diameter of 100–150 mm and is given as

$$R(v) = c(v - A)^b. \tag{2}$$

Where b, c, and A are regression coefficients. On the basis of the damage dataset for the 1995 Kobe earthquake, Isoyama *et al*. (2000) obtained the following result for $R(v)$:

$$R(v) = 3.11 \times 10^{-3}(v - 15)^{1.30}. \tag{3}$$

In addition, for $R(v)$, Eqs. (4) and (5) were proposed by Takada *et al*. (2001) and Tokyo Metropolitan Government (2006).

$$R(v) = 6.33 \times 10^{-5} v^{2.10}. \tag{4}$$

$$R(v) = 2.24 \times 10^{-3}(v - 20)^{1.51}. \tag{5}$$

In this study, the damage ratios of water distribution pipelines following the 2007 Niigata-ken Chuetsu-oki earthquake are compared with Eqs. (3), (4), and (5). The coefficient for the pipe material, C_p, in Eq. (1) is also defined to be 1.0 for the vinyl pipe (VP) on the basis of the damage dataset obtained after the 1995 Kobe earthquake. Therefore, the damage ratios of the CIP and the VP are compared with Eqs. (3), (4), and (5). The damage ratios of the ductile cast iron pipe (DIP) are estimated from Eqs. (3), (4), and (5) by multiplying by C_p, which is set to be 0.3 in the previous study (Isoyama *et al.* 2000).

4. RELATIONSHIP BETWEEN WATER PIPELINE BREAKS AND SEISMIC MOTION INTENSITY DURING THE 2007 NIIGATA-KEN CHUETSU-OKI EARTHQUAKE

4.1. Damage ratio adjacent to seismic observation station

The damage ratios of water distribution pipelines adjacent to seismic observation stations were calculated to compare with the damage ratios obtained from Eqs. (3), (4), and (5). The locations of seismic observation stations considered in this study are shown in Fig. 2. The damage ratios of water pipelines are defined in the area within a radius of 2 km from seismic observation stations and located on alluvial plain. The damage ratios were defined with respect to the pipe materials, i.e., CIP, VP and DIP.

The damage ratios of water distribution pipelines are shown in Table 1 and they are compared with Eqs. (3), (4), and (5) in Fig. 3. It should be noted that the damage ratios of the CIP show the same values for the JR Kashiwazaki Station, K-NET Kashiwazaki, and Kagami-machi gas holder because the area for calculation overlaps. The three observation stations are located close to each other. In addition, the utilization of the CIP is limited to a certain area in Kashiwazaki city, where the three circles with the center of the three stations overlaps. The damage ratio of CIP at Kagami-machi gas holder was adopted in Fig. 3.

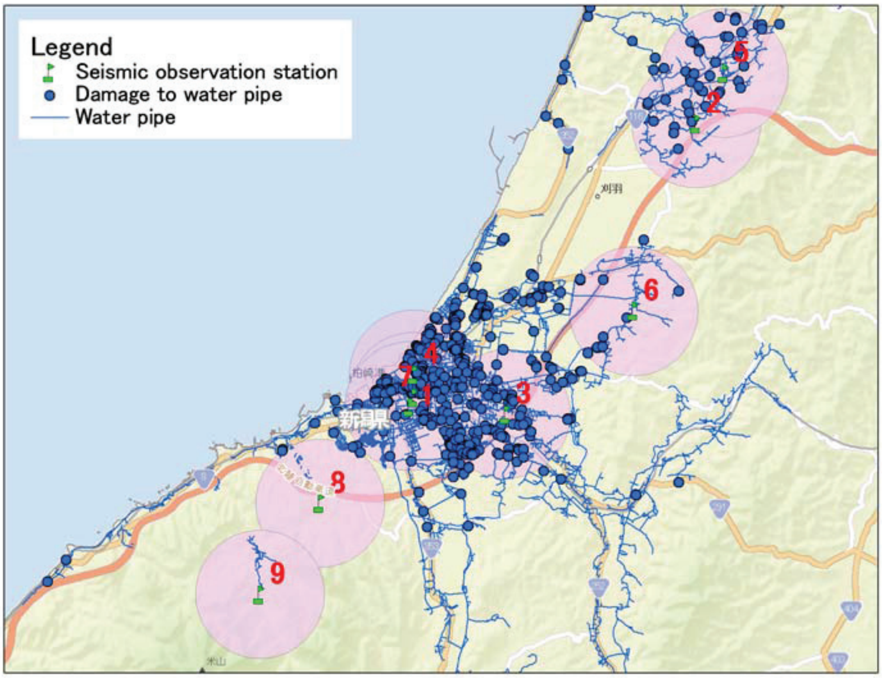
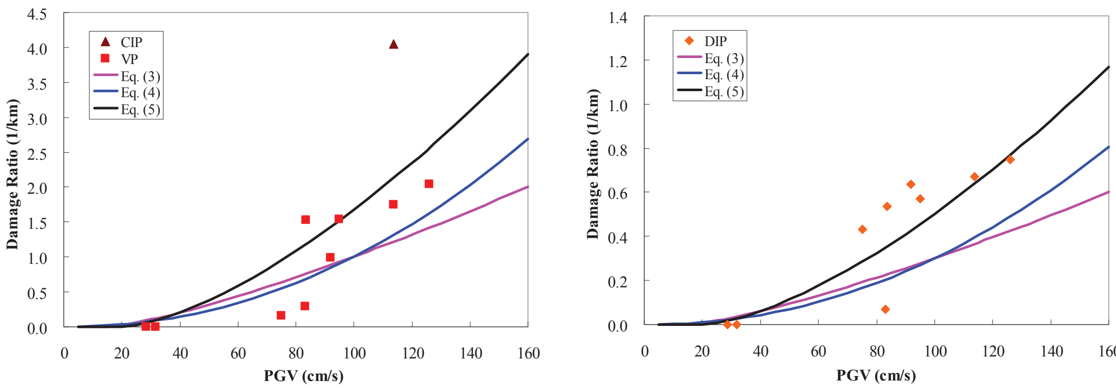


Figure 2: Locations of seismic observation stations in Kashiwazaki City

Table 1: Damage ratios of water distribution pipelines with respect to the material of pipe

No. in Fig. 2	Seismic Observation Station	PGV (cm/s)	CIP			VP			DIP		
			Number of Damages	Length (km)	Damage Ratio (1/km)	Number of Damages	Length (km)	Damage Ratio (1/km)	Number of Damages	Length (km)	Damage Ratio (1/km)
1	JR Kashiwazaki station	95.05	13	3.2	4.04	68	44.1	1.54	60	105.0	0.57
2	Nishiyama IC	75.05	0	0.0	-	1	6.4	0.16	7	16.2	0.43
3	Kashiwazaki IC	91.98	0	0.0	-	31	31.3	0.99	48	75.5	0.64
4	K-NET Kashiwazaki	126.06	13	3.2	4.04	93	45.6	2.04	78	104.2	0.75
5	Nishiyama-cho office	83.53	0	0.0	-	8	5.2	1.53	7	13.0	0.54
6	Yoshii oil plant	83.20	0	0.0	-	2	6.8	0.30	1	14.2	0.07
7	Kagami-machi gas holder	113.71	13	3.2	4.04	83	47.5	1.75	72	107.5	0.67
8	Kawauchi dam	31.77	0	0.0	-	0	0.6	0.00	0	1.7	0.0
9	Tanine dam	28.55	0	0.0	-	0	2.0	0.00	0	1.7	0.0

As for the CIP and VP, the damage ratios in the 2007 Niigata-ken Chuetsu-oki earthquake are higher when the PGV is approximately 80 cm/s or more. The damage ratios in the PGV range of less than 80 cm/s are lower than the estimations according to the three fragility curves. As for the DIP, the damage ratios show higher values than the estimations in the PGV range of 80-120 cm/s.



(a) CIP and VP (b) DIP

Figure 3: Comparisons of damage ratios of water distribution pipelines adjacent to seismic observation stations with the fragility curves for water distribution pipelines.

Table 2: Residual errors for actual damage ratios and the three fragility curves.

Material of pipe	Eq. (3)	Eq. (4)	Eq. (5)
CIP, VP	79.79	65.05	47.01
DIP	42.83	38.61	6.71

The accuracy of the estimations was examined using the following equation (Table 2).

$$\varepsilon = \sum \left(P_R - R(v)\right)^2 w \quad (6)$$

Where P_R and w represent the actual damage ratio and the length of the water distribution pipeline, respectively. According to Table 2, Eq. (5) shows the best estimation for the both cases.

4.2. Distribution of damage incidents in all area of Kashiwazaki city

The nonlinear regression analysis was performed using the damage data in Kashiwazaki city to examine the relationship between the damage ratios of water distribution pipelines and the PGV for a wider area. To achieve the objective, the distribution of seismic motion estimated by Maruyama *et al.* (2010) was used in this study. Figure 4 shows the spatial distribution of the PGV and the locations of damage to water distribution pipelines.

Table 3 shows damage ratios of water distribution pipelines obtained from Fig. 4. The water pipelines located on the alluvial plain were used to obtain the damage ratios in Table 3. The non-linear regression analyses are performed to compare the damage ratios during the event with the three fragility curves.

Equation (7) is adopted to express the damage ratio of water distribution pipelines. The function consists of the three parameters, C, λ, and ζ.

$$R(v) = C\Phi\left(\left(\ln v - \lambda\right)/\zeta\right) \tag{7}$$

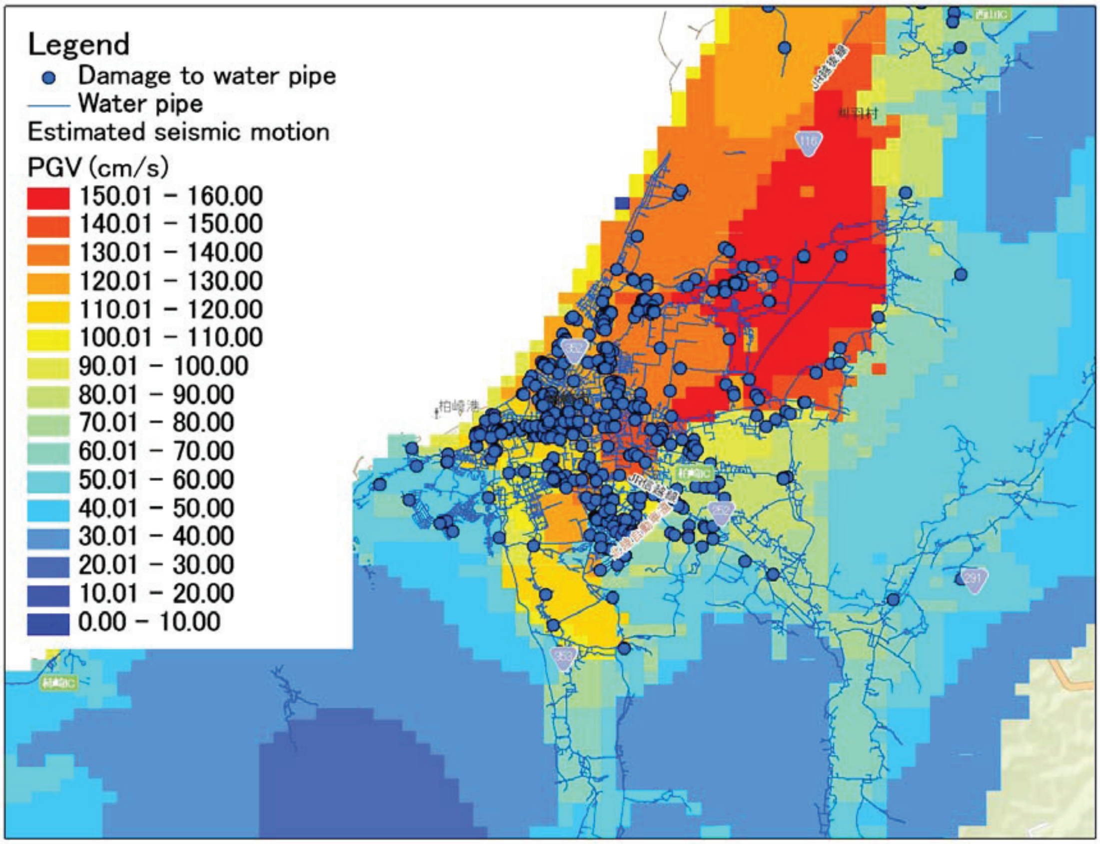


Figure 4: Distribution of the PGV and the locations of damage to water distribution pipelines

Where $\Phi(x)$ is the cumulative distribution function of the standard normal distribution, and λ, ζ, and C are constants determined by a regression analysis. With this formula, only three parameters need to be determined and the lowest PGV that causes damage and the largest damage ratio is not necessary to assign. We thus performed a nonlinear regression analysis to determine the three parameters in Equation (7). The error term ε, shown in Equation (6), was minimized using the quasi-Newton method.

Table 4 shows parameter ζ, λ, and C determined by nonlinear regression analysis. Figure 5 compares the obtained curves with the three functions shown in Eq. (3)-(5). The damage ratios of the DIP after the event were larger than those after the Kobe earthquake in the range of 40-110 cm/s. As for the CIP and the VP, the damage ratios were almost equivalent to those after the 1995 Kobe earthquake. However, these results highly depend on the accuracy of the ground motion estimation, and thus a further study may be necessary till a more reliable fragility curves are obtained.

Table 3: The damage ratios of water distribution pipelines calculated for the entire Kashiwazaki city.

(a) : CIP and VP

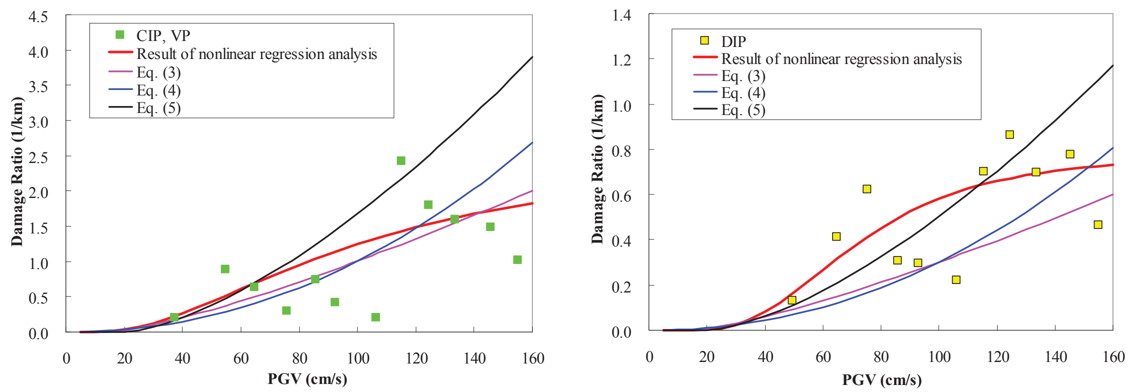
Section of PGV	Weighed mean of PGV (cm/s)	Number of Damages	Length (km)	Damage Ratio (1/km)
-50	37.2	4	19.7	0.20
50-60	54.8	17	19.1	0.89
60-70	64.7	11	17.2	0.64
70-80	75.7	2	6.7	0.30
80-90-	85.7	7	9.5	0.74
90-100	92.4	3	7.1	0.42
100-110	106.4	2	9.8	0.20
110-120	115.2	41	16.9	2.43
120-130	124.4	56	31.0	1.80
130-140	133.5	25	15.7	1.59
140-150	145.8	12	8.1	1.48
150-	155.1	7	6.8	1.02

(b) : DIP

Section of PGV	Weighed mean of PGV (cm/s)	Number of Damages	Length (km)	Damage Ratio (1/km)
-60	40.4	8	60.9	0.13
60-70	64.7	11	26.7	0.41
70-80	75.3	14	22.5	0.62
80-90-	85.9	6	19.5	0.31
90-100	92.8	5	16.8	0.30
100-110	105.9	4	18.2	0.22
110-120	115.6	32	45.6	0.70
120-130	124.4	51	59.0	0.86
130-140	133.5	32	46.0	0.70
140-150	145.3	17	21.9	0.78
150-	155.0	11	23.7	0.46

Table 4: Fragility curve parameters determined by the nonlinear regression analysis.

Material of pipe	ζ	λ	C
CIP, VP	0.723	4.58	2.42
DIP	0.468	4.27	0.76



(a) CIP and VP (b) DIP

Figure 5: Relationship between results of nonlinear regression analysis and fragility curves for water distribution pipelines.

5. CONCLUSIONS

The damage ratios of water distribution pipelines adjacent to seismic observation stations were compared with fragility curves for water distribution pipelines developed after the 1995 Kobe earthquake. The fragility curves proposed by Tokyo Metropolitan Government fit better than the other two empirical curves.

In order to consider the damage ratios in the 2007 Niigata-ken Chuetsu-oki earthquake for a wider area, the spatial distribution of the PGV was employed for investigations. The nonlinear regression analysis was performed to examine the relationship between the damage ratios of water distribution pipelines and the PGV. The damage ratios of the DIP after the event were larger than those after the Kobe earthquake in the range of 40-110 cm/s.

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